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Factors Affecting Automotive Fuel Economy

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U.S. Environmental Protection Agency
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Mobile Source Air Pollution Control
Emission Control Technology Division

Introduction

This is the third EPA report on the subject of automobile fuel economy. The two previous reports were published in November 1972 and October 1973.

The previous EPA reports have been studied and commented upon by other government agencies, the Congress, State and local governments, private citizens, fleet operators, motor vehicle manufacturers, and fuel producers. This report is intended for the same broad audience.

This report contains new information on emission controls and tampering, and the average fuel economy of the 1975 cars. It also includes information on driving patterns and their effect on fuel economy. Thus it should aid drivers as well as car buyers in making choices which can affect their gas mileage.

Summary of Conclusions

1. The most important vehicle design features affecting fuel economy are vehicle weight and engine displacement. A 10% change in either weight or displacement causes a fuel economy change of 3 to 6%. Since weight changes are usually accompanied by displacement changes, the fuel economy effect of both of these changes has sometimes been attributed to weight alone (Section V–C).

2. Vehicle size and weight and the use of power-consuming convenience devices have all been increasing steadily for more than 10 years. Parameters which affect engine efficiency have also been changing, sometimes in directions leading to lower efficiency (Section IV–C).

3. Driving habits and trip characteristics can have more effect on fuel economy than any vehicle design feature. A standard size car can get over 20 miles per gallon under favorable conditions; it can also get less than 2 miles per gallon under poor conditions (Section IV–D).

4. Travel habits in the U.S. lean heavily toward driving conditions which give poor fuel economy. U.S. autos accumulate about 15% of their mileage in trips of 5 miles or less; however, these trips consume more than 30% of the Nation's automotive fuel, because autos operate so inefficiently in short trips (Section IV–D).

5. There is no simple or inherent relationship between fuel economy and the emissions standards that new cars are required to meet; especially misleading is the contention that fuel economy always becomes poorer as emissions standards are made more stringent. With the use of catalyst technology, the average fuel economy of 1975 cars is nearly 14% better than the 1974 models, although their emissions are lower than the 1974's. In fact, fuel economy of the 1975's is as good as cars built before emission controls were introduced (Section V–C).

6. Technology is under development in the laboratory to further reduce emissions without sacrifice in fuel economy from 1975 levels. Considerable engineering development remains before these new technologies are ready for production (Section V–A).

7. There is no guarantee of superior fuel economy through the use of catalytic converters. 1975 cars using catalysts can give excellent or poor fuel economy, depending on the manufacturer's overall design. Cars which do not use catalysts can also give excellent or poor economy, again depending on the overall design (Section V–C).

8. Emission control system tampering by garage mechanics is more likely to hurt fuel economy than to improve it. Such tampering virtually always makes emissions worse, and can cause deterioration in engine durability. Regular maintenance according to manufacturer specifications improves both emissions and fuel economy (Section V–B).

9. Of the many types of alternative engines developed and under development, three types are available in mass-produced 1975 vehicles. When compared to conventionally-powered 1975 cars with similar power-to-weight ratios, present rotary engines suffer a 30% penalty in fuel economy, CVCC engines give about the same economy, and Diesels provide a 35% improvement (Section V–E).

Data Base and Test Procedures

The fuel economy data used in this report came from tests made by EPA, auto manufacturers, the Department of Transportation and other researchers. Each year, auto manufacturers demonstrate that their next model year's vehicles comply with Federal emission standards; they do this by running their own tests and also by submitting pre-production cars for testing by EPA.

In the EPA tests, two separate fuel economy values are determined for each car—one for city and one for highway driving, so each motorist can evaluate fuel economy potential according to his own mix of urban and highway travel. The average U.S. motorist travels 55% of his mileage under urban conditions and 45% on the highway.

The city test procedure is a 7.5 mile stop-and-go driving cycle with a speed range from zero to 57 MPH and an average speed of 20 MPH. The trip begins with a cold start,[1] takes 23 minutes, and has 18 stops. 18% of the trip time is spent idling during these stops. The first 8-minute segment of the trip is then repeated from a hot start,[2] and test data are combined to represent a realistic mixture of hot and cold start urban driving.

The highway test procedure simulates a 10 mile non-stop trip with an average speed of 48 MPH. The trip begins with a hot start and lasts 13 minutes. Except for starting and finishing at a standstill, the speed range is 28 to 60 MPH.

The cars are tested indoors by professional drivers on a chassis dynamometer, a machine that reproduces the operation of a vehicle under various driving conditions. Use of a dynamometer, rather than road tests, allows the tests to be conducted in exactly the same way each time.

Fuel economy is calculated from measurements of the amount of fuel consumed during a test of known length (miles). This measurement can be done by before-and-after fuel weighing, by using flow meters in the fuel line, or by measuring the amount of carbon in the exhaust (since exhaust carbon originates in the gasoline, the amount of fuel used can be computed).

When performed correctly, any of these techniques are acceptably accurate. EPA uses all three methods, but relies primarily on the carbon technique. (See Appendix A).

These test procedures compare well with driving patterns measured in actual traffic; they also compare well with gas mileage tests used by the auto industry. The fuel economy values from these tests are in reasonable agreement with statistics on national fuel consumption.

Two notes of caution:

(a) Many of the fuel economy values in this report are average values for a number of vehicles in a given class: An individual car run through the same tests might give fuel economy results above or below the average for its class, depending on its engine, transmission, axle ratio, accessories, etc.

(b) Reported test results are no guarantee of the fuel economy a motorist will get in actual driving. An individual car operated by its owner can deliver fuel economy different from the official test values if the type of driving he does differs significantly from the city and highway cycles used in the EPA tests.

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[1] Engine is started after vehicle has been parked overnight.

[2] Engine is started while still hot.

Contents

Factors Affecting Auto Fuel Economy

Fuel Economy, expressed in miles per gallon (MPG), is an index of the overall "effectiveness" achieved with a motor vehicle which consumes fuel. It measures what you get (miles traveled) versus what you put in (gallons of fuel). It is related to engine power load, vehicle speed, and engine efficiency. (See Appendix B for a more detailed explanation.)

For a given speed and engine efficiency, fuel economy is high for low power requirements and decreases as power goes up. For a given speed and power load, economy is directly proportional to efficiency.

Factors Which Affect Engine Power Load

To move a car, an engine must provide power to overcome the following vehicle loads:

- Rolling friction
- Aerodynamic drag
- Inertia (resistance to speed changes)
- Drive train losses
- Accessories

Figure 1 illustrates the relative contribution of these loads for several car sizes under steady speed cruise conditions (where there is no inertia effect).

Figure 2 shows the effect of cruise speed on these variables for a standard size car. Note that rolling friction predominates at low speed, while aerodynamic drag is the largest load at high speeds.

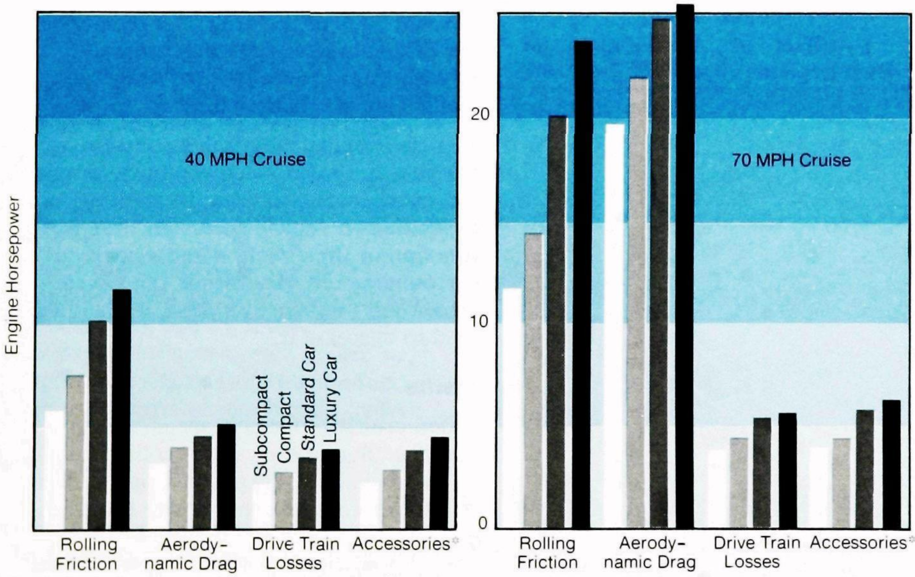
Rolling Friction

Rolling friction is the power lost in tires and bearings. It depends on vehicle weight, speed, and tire characteristics.

At any speed, doubling the weight will double the rolling friction. For any weight, doubling the speed will increase the friction a little more than double, as shown in Figures 2 and 3.

As seen in Figure 3, radial tires can have up to 20% less rolling friction than bias-belted tires when tested on typical road surfaces. Tire pressure can also affect rolling friction: higher pressures provide reduced friction. However, inflation of tires to pressure higher than the manufacturer's recommendations can cause increased tire

Figure 1—Effect of Car Size on Power Requirements



*Includes fan and alternator for all car sizes, power steering for two largest cars; does not include air conditioning.

Figure 2—Effect of Speed on Power Requirements (Standard Size Car)

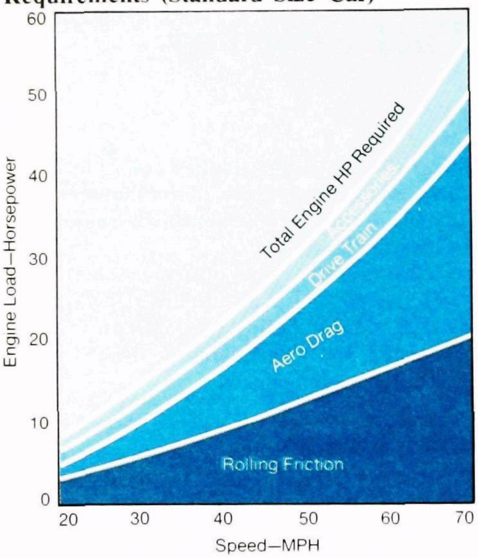


Figure 3—Rolling Friction for Three Tire Types (Standard Size Car)

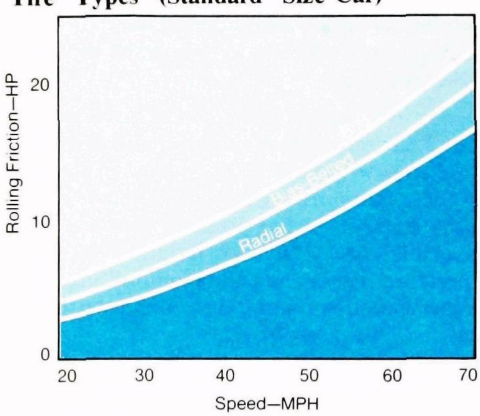
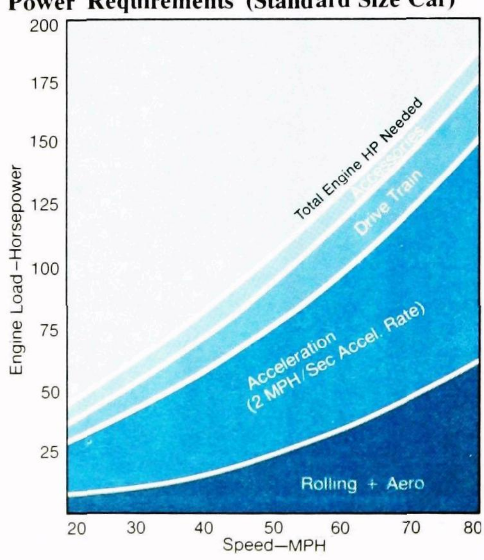


Figure 4—Effect of Acceleration on Power Requirements (Standard Size Car)



wear as well as a harder ride and increased suspension system stresses.

Aerodynamic Drag

The power needed to force an automobile through the air is a function of speed, and the size and shape of the vehicle. The effect of speed is quite pronounced, as shown in Figures 1 and 2. The most significant *size* factor is vehicle frontal area.[3] The frontal area of modern cars is not in direct proportion to weight, i.e. 5000 lb. cars do not have twice the frontal area of 2500 lb. cars. The four car sizes that were used to calculate the power requirements in Figure 1 show this effect:

Table 1

	Curb Weight, pounds	Frontal area, Sq. Ft.
Subcompact	2500	17.5
Compact	3200	19.0
Standard	4400	21.5
Luxury	5300	22.5

The influence of vehicle *shape* is represented by a factor called "drag coefficient", which is lower for more streamlined shapes. The cars of the early 1930's, for example, had drag coefficients of about 0.70, which means the air drag on these cars was 70% of the drag on a rectangular box of the same overall dimensions. Today's cars generally have drag coefficients of less than 0.50.

Surface irregularities such as outside mirrors, sun roofs, open windows, campers, etc. cause increased drag. In addition to depending on vehicle speed, air drag is a function of the direction and velocity of the surrounding air. Headwinds (and even crosswinds) increase air drag, and tailwinds tend to decrease it.

Inertia

When cruising at steady speed, the only forces acting on the car are rolling friction and aerodynamic drag, but if one wishes to accelerate, additional power must be

[3] The cross-section area of the car as viewed from the front.

provided to "push" the mass of the car to higher speeds.

Figure 4 shows this increase in power for a two MPH/Second acceleration. Even this mild acceleration can result in power requirements more than triple that of steady speed cruising.

Drive Train Losses

The power required to overcome rolling, aerodynamic, and inertial loads must be transmitted from the engine to the drive wheels by the drive train (transmission and differential/axle). Inefficiencies in the drive train components represent a power loss which must be made up by the engine.

The differential/axle and the transmission gearbox each contribute about a 3% loss. Additional losses occur with automatic transmissions due to the torque converter and transmission oil pump. The total losses for automatic transmission drive trains are approximately as follows for a standard size car:

Table 2

	Wheel HP	Drive Train Loss, HP
20 MPH	4.97	1.24 (25%)
40 MPH	14.4	3.17 (22%)
60 MPH	31.7	5.09 (16%)
80 MPH	60.0	7.99 (13%)

Accessories

In this report, the term "accessories" is used to describe both necessary engine auxiliaries (fan, alternator) and convenience devices (power steering, air conditioning).

Accessories can add to vehicle power requirements in two ways: by consuming power themselves, and by adding weight. For four particular accessories, power consumption outweighs the weight effect: these are the alternator, engine fan, power steering and air conditioning. This is illustrated in the table below for a 30 MPH cruise:

Power-consuming accessories are more prevalent in large cars than small ones, as shown in Figure 5.

Table 3

	Increase over 30 mph cruise HP* — Due to Accessory Weight	Increase over 30 mph cruise HP* — Due to Accessory Power
Fan	0.1%	2%–3%
Alternator	0.2%	5%–20%
Power steering	0.3%	5%–9%
Air conditioning	1.2%	30%–50% (85°F)

* The % decrease in fuel economy is about 2/3 of the % increase in HP.

Factors Which Affect Engine Efficiency

As shown in the previous section, the mechanical output of an engine must overcome vehicle power loads such as rolling friction, aerodynamic drag, etc. But when fuel is burned in the cylinders of an engine, only part of the combustion heat energy is converted to mechanical power; the rest of the heat is carried away by the cooling water and the hot exhaust.
Figure 6 shows how the total combustion energy splits between mechanical power and waste heat under cruise conditions.

The "efficiency" of an engine defines the fraction of the combustion heat which ends up as mechanical power output. Modern

Figure 5—Accessory Installation vs. Vehicle Curb Weight

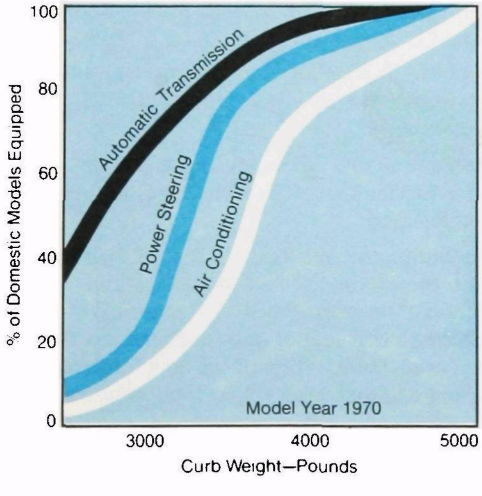


Figure 6—Heat Energy Distribution, Full Size Auto Engine

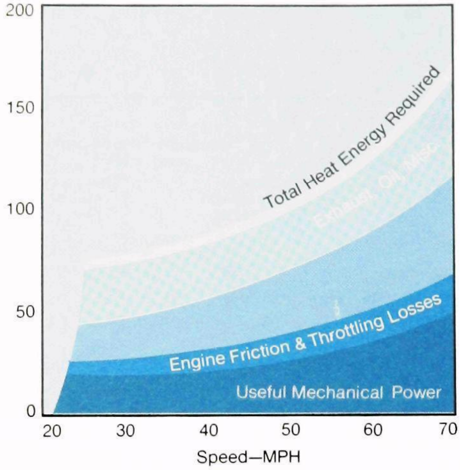
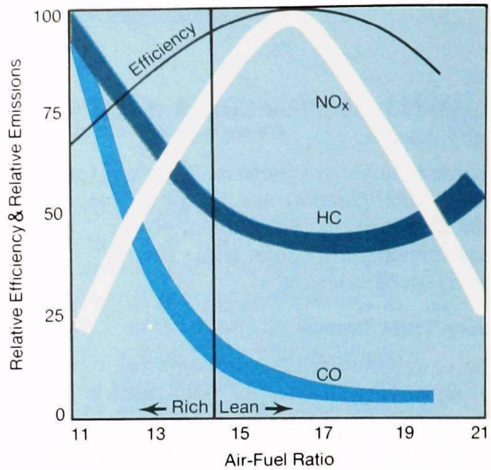


Figure 7—Effect of Air-Fuel Ratio on Efficiency and Emissions



auto engines operate at efficiencies from about 10% to 30%, depending primarily on the following factors:

- Air-fuel ratio (carburetion)
- Compression ratio
- Engine load factor
- Engine speed (RPM)
- Spark timing

Many other design features influence efficiency, such as number of cylinders, bore and stroke dimensions, number of rings, valve size, etc. but these are generally overshadowed by the above variables.

Air-Fuel Ratio

Gasoline engines are usually most efficient at air-fuel ratios slightly above the stoichiometric (chemically balanced) value,[4] shown in figure 7. In non-stoichiometric mixtures, there is either excess fuel (rich) or excess air (lean) present in the combustion chamber but not entering into the combustion reaction, and efficiency is lowered.

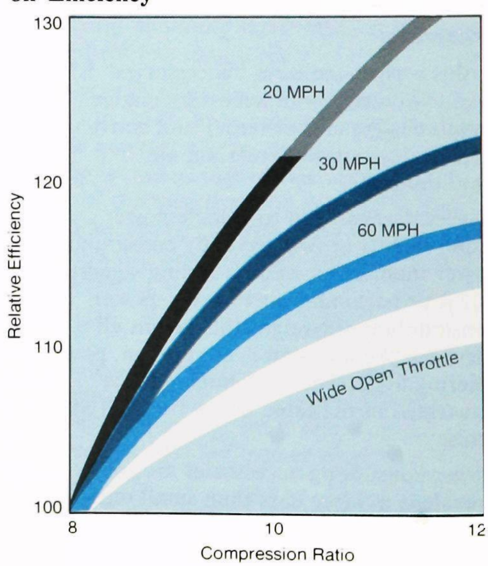
The peak of the efficiency curve can be shifted to leaner air/fuel ratios with engine modifications.

The figure also shows the effect of air-fuel ratio on emissions. Hydrocarbons and carbon monoxide emissions generally decrease with leaner mixtures due to the increased availability of oxygen. Nitrogen oxide emissions peak where temperature and oxygen concentration are both relatively high. This is somewhat leaner than where peak temperature occurs (~13:1) and somewhat richer than the leanest mixtures attainable.

Compression Ratio

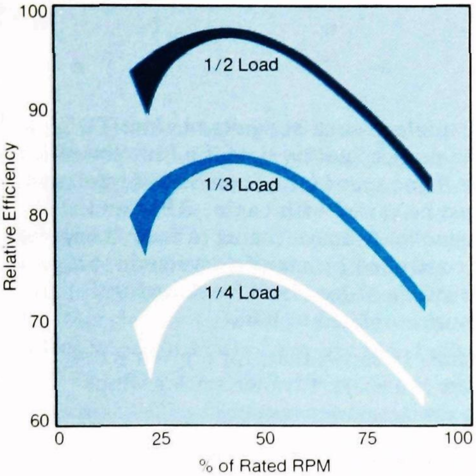
Higher compression ratios promote higher peak temperatures and lower exhaust temperatures, and hence greater conversion of the fuel's heat energy into mechanical work. The influence of compression ratio on efficiency varies with the engine's operating condition. At low speeds, the

Figure 8—Effect of Compression Ratio on Efficiency



[4] This value is a little less than 15 parts air to 1 part fuel, by weight.

Figure 9—Effect of Load Factor on Efficiency



compression ratio effect is more pronounced than at high speed, as shown in Figure 8.

Since higher compression ratios increase engine power capability, an additional efficiency benefit can be achieved by using a lower-displacement engine; this holds vehicle performance constant. Figure 8 includes this effect.

Engine Load Factor

As an engine's power level is reduced, it operates less efficiently, as seen in Figure 9. This occurs because a relatively closed throttle is a barrier in the intake, and the piston has to work harder to suck in the fuel and air past this obstruction.

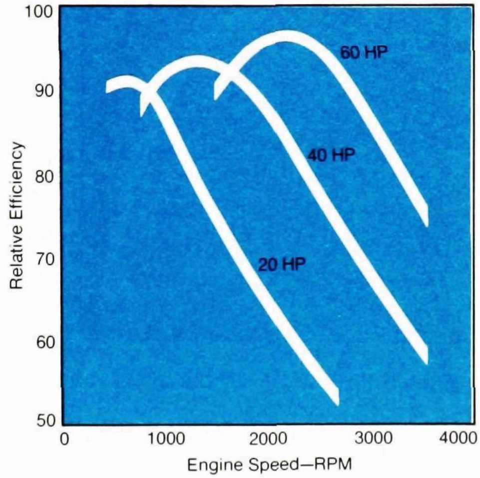
Also, when an engine is operated at low power, it wastes a higher fraction of its total power on internal friction, which is essentially constant for a given RPM.

Of course, running an engine at a higher power level will not produce better *fuel economy,* even though it may make it operate more efficiently; a power increase always overshadows the efficiency gain it produces. *For a given speed and load,* a small engine operating at a high load factor will have higher efficiency *and* better fuel economy than a larger engine running at a low load factor.

Engine Speed

Figure 9 shows that efficiency depends on engine RPM. This is more fully illustrated in Figure 10, which shows the effect of speed on efficiency for several fixed power levels.

Figure 10—Effect of Engine Speed on Efficiency



A decrease in engine speed usually increases efficiency. This occurs because lower speeds give lower internal engine friction and lower throttling losses.

The fuel economy effect of this can be seen in actual practice when an engine is run slower by means of lower axle ratios and/or overdrives.

Spark Timing

An engine operates most efficiently when peak combustion pressure is reached just after the piston passes top dead center (TDC) position. To achieve this, the fuel-

Figure 11—Effect of Spark Timing on Power

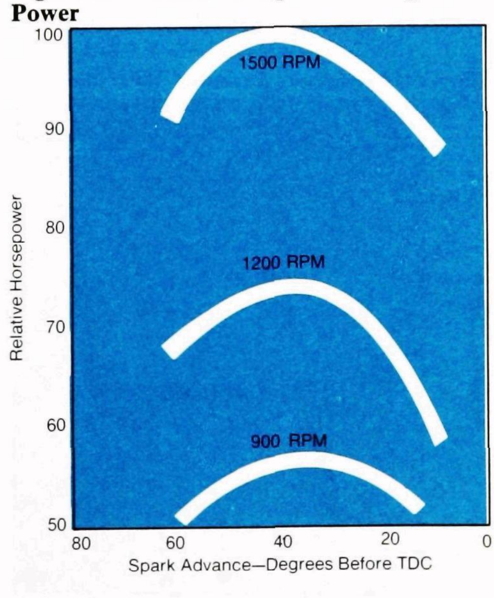


Figure 12—Effect of Spark Timing on Efficiency

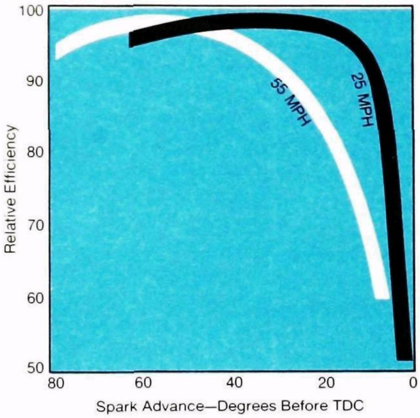


Figure 13—Curb Weight Trends by Market Class, U.S. Sales

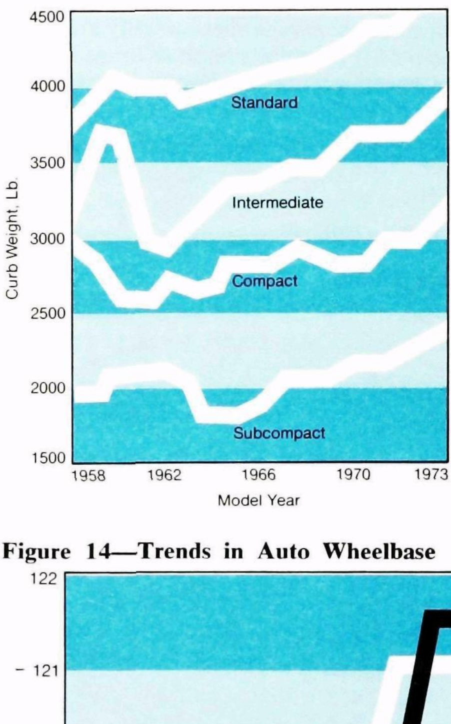
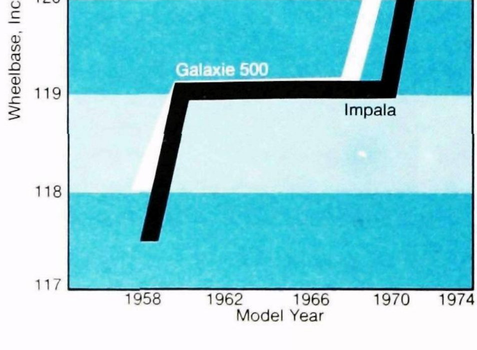


Figure 14—Trends in Auto Wheelbase



air mixture must be ignited before TDC. The proper ignition time is a function of the flame speed in the combustible gas, and must be varied with engine RPM and engine load. Spark timing in today's engines is controlled by manifold vacuum, an indication of load; and by centrifugal advance, related to RPM.

Figure 11 shows that, for a given RPM, there is a spark advance setting which maximizes power output.

The effect of spark timing on efficiency appears in Figure 12 for two cruise speeds. As with power output, maximum efficiency occurs at some particular advance setting.

The amount of advance shown for these driving conditions should not be confused with idle spark advance, which is normally just a few degrees.

Spark timing is similar to compression ratio: too much spark advance will cause knocking unless higher octane fuel is used.

Trends in Car and Engine Design

Many vehicle design factors have changed notably in the last several years. Many of these changes have had adverse effects on fuel economy. Fuel economy is not ignored by car designers, but many changes which reduce gas mileage have been made in response to requirements (real or anticipated) in other areas. Because automobile design and development decisions must be made several years prior to actual production, the designer has to guess far in advance what the consumer, economic and government requirements will be; the automobiles in any particular model year are always the result of compromises, tradeoffs, and design judgments.

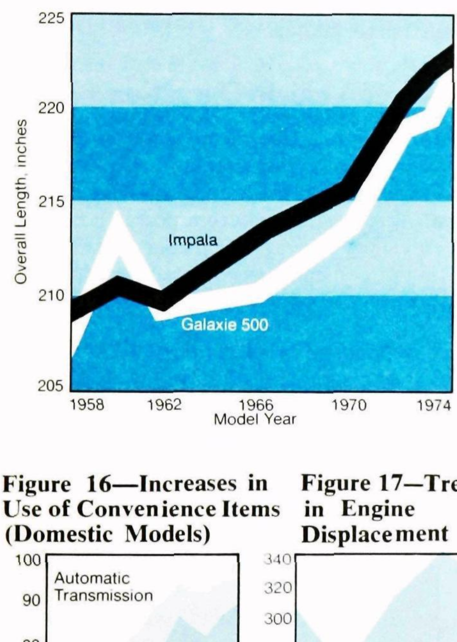
Trends Affecting Power Requirements

In the past 15 years or so, most car lines have changed in ways which increase power requirements. The most obvious of these is vehicle weight. As shown in Figure 13, vehicles offered for sale in the U.S. have been generally gaining weight at a rate of 50 to 100 pounds per year. The average weight of the compact and intermediate classes dipped in the early 1960's due to the introduction of new, lighter-weight models (Falcon, Corvair. Chevy II). but has increased steadily since then. The subcompact class was at its lightest in 1964 due to the high sales fraction of imports, but this class has grown in weight since the introduction in 1970 of heavier U.S. built models (Gremlin, Pinto, and Vega).

Note that 1973's subcompacts are nearly as heavy as 1962's compacts, 1973's compacts are as heavy as 1962's intermediates, etc.

In every one of the 11 years from 1958 to 1968, the best-selling test weight class was 4000 pounds; in 1968 it jumped to 4500 pounds and for 1975 the projected best-selling class is 5000 pounds. Fortunately, *average* weight for the whole U.S. market has gained only about 25 pounds per year through 1973, because of the increased sales penetration of the light weight classes.

Figure 15—Trends in Auto Length



Car dimensions have been increasing too. Figures 14 and 15 illustrate the trends in wheelbase and length for the best-selling standard size cars. This rate of increase in dimensions is typical of all market classes. Since some observers have linked growth in vehicle size to government safety regulations, note in Figure 15 that these cars grew 14 to 15 inches longer from 1958 to 1972—presumably due to styling choices —but they grew only 3 to 4 inches from 1972 to 1974—when increased crashworthiness was first required in auto bumpers.

In addition to increases in car size, there has been a rising demand for convenience items which increase both vehicle weight and power consumption. Figure 16 shows this trend for those luxury items best known for their high power requirements.

Figure 16—Increases in Use of Convenience Items (Domestic Models)

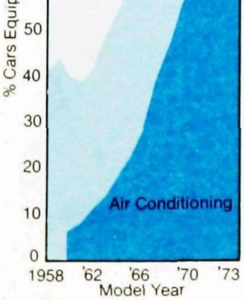
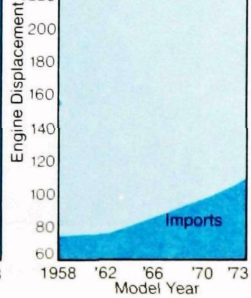


Figure 17—Trends in Engine Displacement



Trends Affecting Engine Efficiency

Figure 17 illustrates how average engine size has changed in the U.S. market since 1958. The drop in the early 1960's for domestic models resulted from the introduction of new compacts and intermediates.

From 1962 to 1970, average engine displacement rose faster than average vehicle weight—a reflection of a general trend toward higher performance. Figure 18 shows that there is a large disparity between the way domestic cars are powered, compared with imports; this disparity has not changed much in 15 years.

Detailed engine design features have been changing also. As seen in Figure 19, the average compression ratio of domestic cars declined due to high volume economy car sales, then rose sharply until the desirability of operating with lower octane gasolines turned it back downward. Compression ratios of the imports, for a long time lower than the domestics, have now risen to comparable values.

As an illustration that auto engine design changes have been going on for years, consider Figure 20 which shows the sudden mid-50's change in the average bore-to-stroke ratio for domestic engines. The old long-strokers gave way to higher RPM short-stroke machines, to provide better breathing, less engine friction, and snappier vehicle performance.

Effects of Vehicle Operation

The foregoing section discussed separately the variables affecting load and efficiency; it is useful now to examine vehicle operating situations wherein power level and efficiency interact. Consider a car cruising at constant speed versus accelerating through the same speed:

This example shows how a large power increase can significantly diminish fuel economy, although engine efficiency nearly doubles. It also shows how much acceleration rate can affect fuel economy.

Figure 18—Trend in Engine Size vs. Vehicle Weight

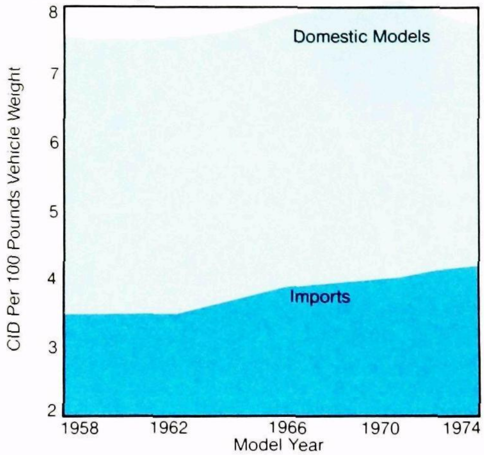


Figure 19—Trends in Compression Ratio

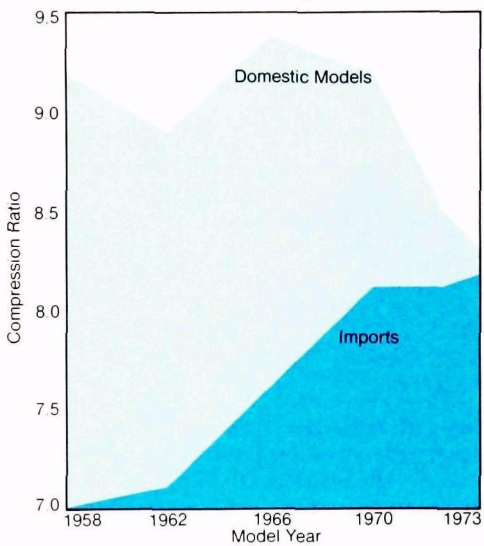


Figure 20—Trends in Engine Bore and Stroke

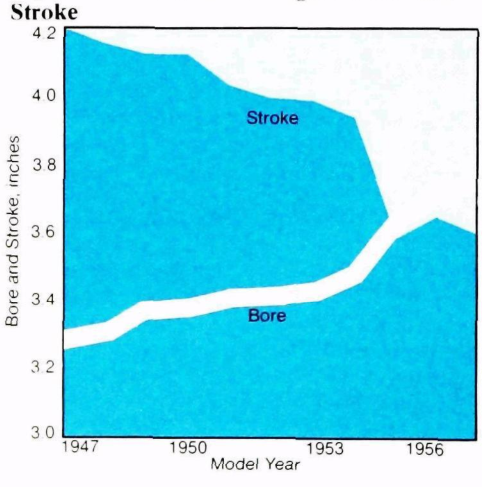


Figure 21—Average Trip Speed vs. Trip Distance

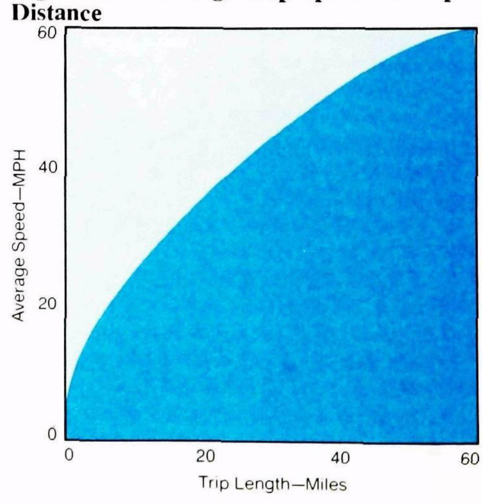


Table 4

	Cruise 22.5 MPH (3rd Gear)	Accelerating 20→25 MPH 2 MPH/Sec (3rd Gear)	4 MPH/Sec (2nd Gear)
Avg. MPH	22.5	22.5	22.5
Avg. RPM	1100	1100	1650
Avg. HP	8.5	40.5	67.9
Efficiency	16%	27%	27%
MPG	20.0	6.9	4.0

The example in Appendix B comparing a 50 MPH cruise and a 70 MPH cruise also illustrates the tradeoff between power and efficiency, with the higher power case again coming out second best in fuel economy.

Since the way a car is driven can make such differences in fuel economy, it is worthwhile to look at the driving patterns actually used by motorists in the U.S.

Characteristics of Trip Patterns

Trip patterns have been studied extensively by the U.S. Department of Transportation, the U.S. Environmental Protection Agency (EPA), auto manufacturers, the Society of Automotive Engineers (SAE), and others. These studies have found that trip length has a large effect on average trip speed, as shown in Figure 21.

This occurs because most long trips are usually taken on the highway while shorter trips tend to involve more urban travel, with a higher frequency of stops.

In fact, there is a direct correlation between frequency of stops and the average speed of the trip, as illustrated in Figure 22. The line in this figure comes from measurements taken in actual traffic. The figure also shows the average speed and stop frequencies for test procedures developed by EPA, the SAE, and a major auto manufacturer. While the average speeds of these procedures vary, they all correlate well with the traffic measurements.

The fuel economy effects of these varying trip characteristics appear in Figure 23, for a standard size car and a compact. Economy under cruise conditions for the same cars is also shown for comparison. Low speed cyclic (stop-and-go) driving gives lower economy than steady speed driving, because of all the accelerations in these driving patterns. At higher speed, the cyclic MPG is closer to the cruise MPG, but still drops off because high speeds give less economy than lower speeds.

Another trip characteristic which influences fuel economy is the warmup effect illustrated in Figure 24. The data were taken by driving over the same one-mile road course for varying distances, each run being made from a cold start. Economy improves

Figure 22—Stopping Frequency vs. Average Speed for Cyclic Trips

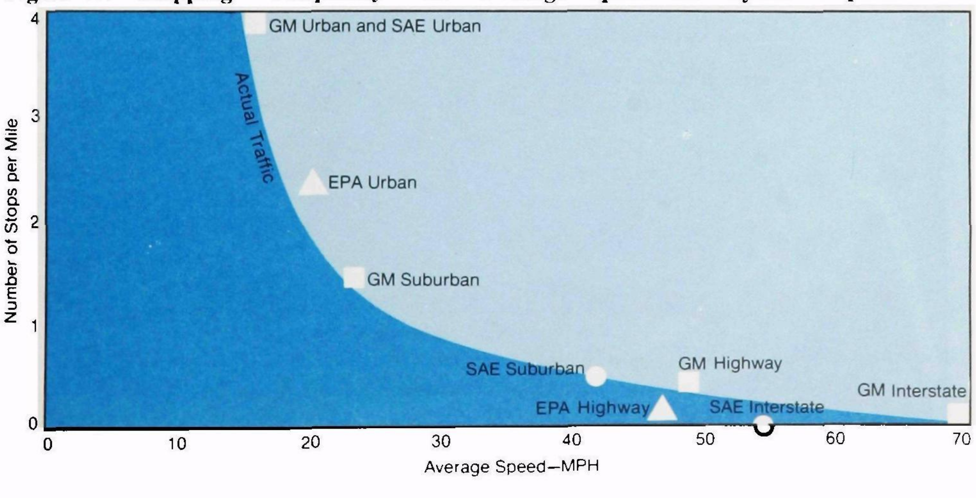


Figure 23—Influence of Driving Pattern on Fuel Economy

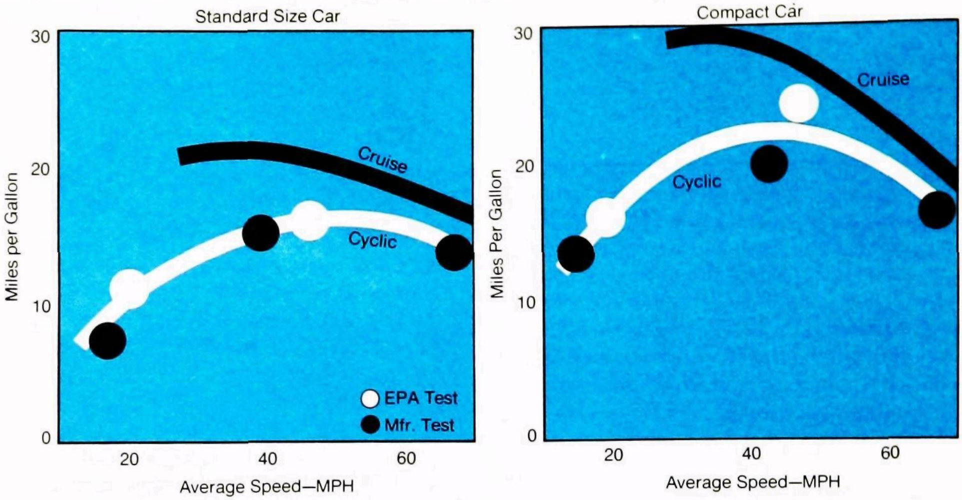


Figure 24—Effect of Trip Length on Cold-start City Fuel Economy

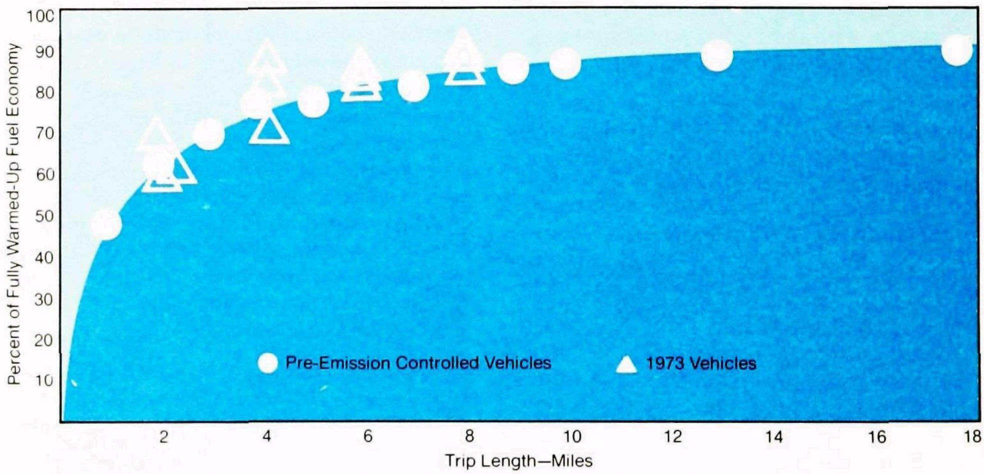
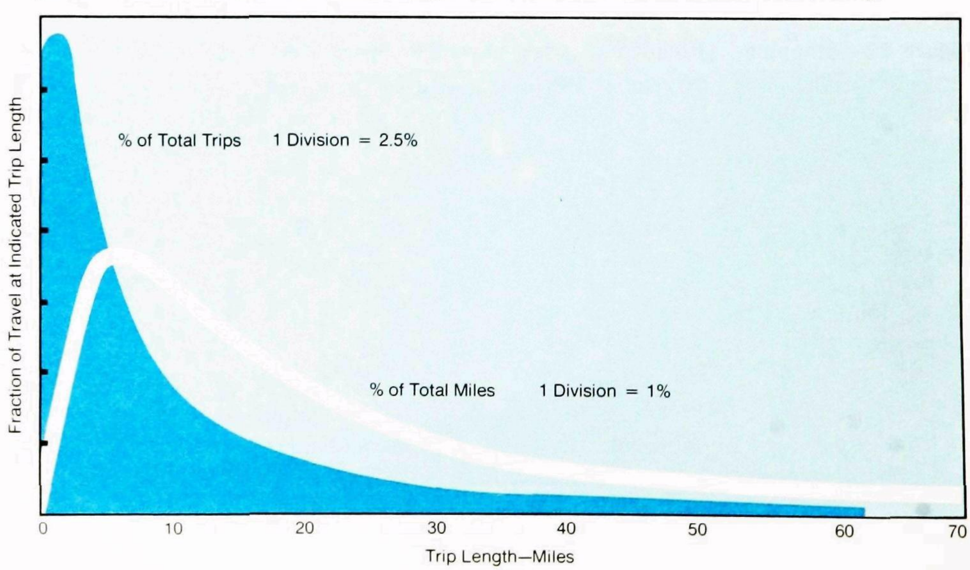


Figure 25—Distribution of Auto Trips and Vehicle Miles Traveled (1970)



with distance traveled because:
(a) rolling friction decreases as tires warm up and inflation pressures rise;

(b) lubricants warm up and friction decreases in the engine and transmission;

(c) carburetion gets leaner (less choke) as the engine becomes hotter; and

(d) less combustion heat is lost to the combustion chamber walls and coolant after they warm up.

U.S. Travel Habits

In Figure 25 we see the results of some of the trip pattern studies mentioned earlier. Short trips overwhelmingly outnumber long ones; the most frequently made car trip is about one mile long. Because the most frequent trips are so short, the distribution of miles traveled peaks at a higher trip distance (5 miles) than the trip distribution, as shown by the dashed curve. This means that more total mileage is accumulated with 5-mile trips although twice as many one-mile trips are taken.

Applying the data on economy vs. speed and trip length to the distribution of trips, we find that a significant amount of travel in the U.S. is made under poor fuel economy conditions.

The mileage and fuel consumption effects of this are summarized in Figure 26, which shows that trips of 5 miles or less make up 15% of miles driven but consume more than 30% of all auto fuel.

Cost to the Individual Motorist

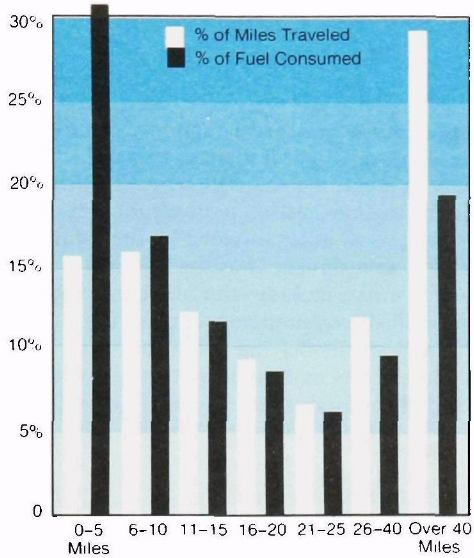
Due to the fuel economy effects of trip length, a typical family car can take the following trips on 25 gallons of gas:

Ten 40-mile trips, or
Sixty 4-mile trips, or
Ninety 2-mile trips, or
One hundred 1-mile trips.

At 75¢ per gallon, the fuel costs would be:

4.7¢ per mile on 40-mile trips, or
7.8¢ per mile on 4-mile trips, or
10.4¢ per mile on 2-mile trips, or
18.8¢ per mile on 1-mile trips.

Figure 26—Distributions of Trip Mileage and Fuel Consumption



Weather and Road Conditions

The section on engine power loads mentioned how wind conditions affect vehicle power requirements by changing air drag. Other conditions which can influence fuel economy are listed below, with their economy penalties based on steady speed cruising at about 50 MPH.

Road Conditions:	**MPG loss**
Broken & patched asphalt	15%
Gravel	35%
Dry sand	45%
3% Grade	32%
7% Grade	55%
Environment:	
18 MPH tailwind (19% gain)	
18 MPH crosswind	2%
18 MPH headwind	17%
50°F ambient temperature	5%
20°F ambient temperature	11%
Altitude (4000 ft)	15%
State of Vehicle Maintenance:	
One plug misfiring 50% of time	7%
Tires underinflated 35%	7%
Front wheels 1/4 inch out of alignment	2%

Combining The Influencing Factors

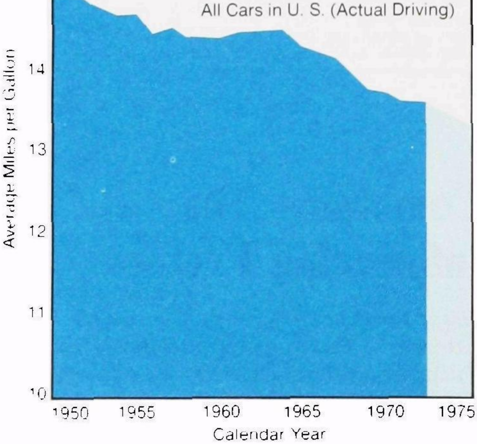
Power loads . . . efficiency . . . driving patterns . . . these are the ingredients of which fuel economy is made. This section will discuss the results of the ways these ingredients have been combined.

Figure 27 illustrates fuel economy trends observed over the last quarter century. The solid curve shows the Federal Highway Administration's estimate of total miles driven by U.S. autos, divided by the total fuel they consumed. Thus the "actual driving" curve includes the fuel consumption of all the old and new cars on the road, and all the driving conditions they encounter: city and highway trips, weather and road conditions, etc. National gas mileage dropped about 9.4% in the 22 years shown.

Figure 28 shows the city fuel economy of new cars for the last nine model years, as determined from EPA city mileage tests. From 1967 to 1974, new cars lost 11.2% in economy, while average new-car weight climbed (7% for domestics, 17% for imports), displacement rose (domestics 6%, imports 29%), air conditioning usage increased sharply (38% of domestic 1967's vs. 70% of 1974's), and emission standards were legislated by Congress. More often than not, the fuel economy loss has been attributed to the emission standards. Indeed, the economy trend seemed to parallel the gradually-tightening emission standards, as shown in Figure 28.

But in 1975 the pattern was broken; the

Figure 27—Trends in Fuel Economy—All U.S. Cars



1975 emission standards are the toughest ever, but fuel economy has never been better.

This calls for a closer look at recent developments related to emissions and fuel economy.

Emission Controls

While much has been said about the effect of emission controls on automobile fuel economy, a review of the available control techniques shows that some can improve economy, some can degrade it, and some have no effect. Whenever fuel-efficient techniques are chosen, emission control need not result in fuel economy losses.

There are three types of automotive emissions:

- Evaporative losses—consisting of raw fuel vapor escaping from the fuel tank, carburetor, and any leaks in the fuel system;
- Crankcase vent gases—consisting of blow-by combustion gases escaping past the piston rings into the crankcase.
- Exhaust pollutants—consisting of unburned hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx), along with a host of other compounds emitted in smaller amounts.

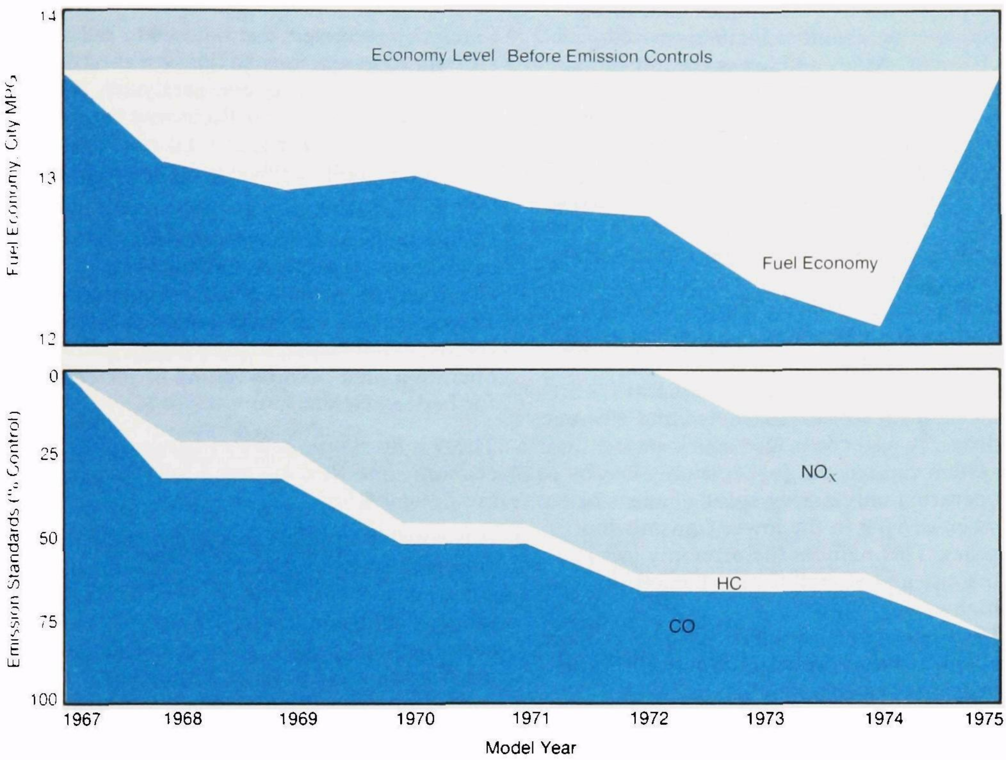
Evaporative and Crankcase Emissions

Evaporative emissions have been controlled since 1971 [5] through the use of modified gas tanks, sealed gas tank caps, and activated charcoal canisters which store fuel vapor during engine shutdown and release it into the air cleaner for combustion when the engine is operating.

Crankcase ventilation has always been required in internal combustion engines, to relieve pressure build-up in the crankcase and reduce the sludge-forming and oil dilution effects of blow-by gases, water vapor, and unburned fuel vapor.

[5] Standards for controlling evaporative emissions were first put into effect in 1970 in California and 1971 nationwide

Figure 28—Fuel Economy vs. Model Year (Fixed Model Mix, Sales Weighted)



Since the early 1960's, all new cars use positive crankcase ventilation (PCV) systems which route crankcase vapors into the engine's intake manifold.

Exhaust Emissions

A variety of techniques are available for controlling exhaust emissions. Modifications in the fuel and air intake systems and within the combustion chamber reduce the formation of pollutants in the combustion process. Other techniques function in the exhaust to clean up pollutants which remain after combustion. The most common of these techniques are discussed below.

Fuel/Air Induction Modifications

Techniques frequently used upstream of the combustion chamber include intake manifold modifications to promote better fuel/air distribution, intake air heating, early fuel evaporation, improved chokes, improved carburetion, and exhaust gas recirculation (EGR). The first five are usually combined to permit leaner combustion, which decreases HC and CO emissions. Up to a point (Figure 7), lean combustion also increases fuel economy.

Exhaust gas recirculation decreases NOx formation by lowering peak flame temperature during combustion. EGR can either improve or degrade fuel economy: if excessive exhaust gas is recycled at light loads, flame speed slows down and engine efficiency is impaired; misfire can also result. On the other hand, properly controlled EGR systems can maintain or even improve fuel economy by reducing throttling and allowing higher compression ratios and/or increased spark advance with no change in fuel octane.

Combustion Modifications

Emission control techniques used in the combustion chamber include revised chamber shapes and lower compression ratios. The latter permits use of lower octane, low-lead or no-lead fuels; the resulting lower peak flame temperatures and higher exhaust temperatures reduce HC and NOx emissions, but efficiency suffers. Spark retard is often used to control emissions. Late combustion reduces peak temperatures, and hence NOx formation, and increases exhaust temperature. The hotter exhaust promotes oxidation of HC and CO downstream of the cylinders. As with lower compression ratios, less mechanical work is extracted and efficiency drops. A well-controlled spark retard system can cut the fuel economy loss by operating only during speed changes or when driving in the lower transmission gears. This reduces the economy loss in the city and eliminates the loss on the highway.

High-energy ignition has no direct economy effect, but can promote leaner A/F ratios and improve engine reliability.

Post-Combustion Chamber Modifications

Techniques used downstream of the combustion chamber include enlarged exhaust manifolds, thermal reactors, catalytic converters, and air injection. All of these techniques promote chemical conversion of exhaust pollutants to relatively harmless compounds; the devices themselves do not affect fuel economy.

Revised manifolds and thermal reactors both provide increased residence time of the hot exhaust gases, promoting further oxidation of the HC and CO leaving the combustion chambers.

Because excess oxygen is required, systems with thermal reaction manifolds use either lean combustion or rich combustion plus air injection. Since thermal reaction efficiency depends on temperature, timing and carburetion calibrations may be used to get high exhaust temperatures, and the fuel economy effects of these may show up in connection with thermal reaction emission controls.

Catalytic converters can be used to reduce HC and CO emissions (oxidation catalysts), NOx emissions (reduction catalysts), or all three (dual catalysts or three-way catalysts). Oxidation catalysts are the only ones with proven durability sufficient for incorporation in 1975 cars.

Unlike thermal reactors, oxidation catalysts can reduce HC and CO emissions effectively at normal exhaust temperatures. These catalysts can make emission control relatively independent from engine operation, and permits tuning of the engine for better efficiency.

There is no simple relation between fuel economy and the emission levels that cars are designed for.

It is possible to utilize any given combination of emission control techniques and engine design specifications over a broad range of emission levels, through adjustment of design features and operating conditions (e.g. spark timing and carburetor adjustments). Fuel economy will also vary with the adjustments made for emissions control.

Unfortunately the optimum fuel economy is usually reached before the full emissions control potential of the technology is realized, so that pushing a given technology to its ultimate emissions control potential will result in a fuel economy lower than optimum. For example, prior to 1975, auto manufacturers controlled emissions mainly through engine modifications. This resulted in a reduction in fuel economy—especially for large cars—from the optimum fuel economy achievable with that particular technology.

However, with the effective use of 1975 catalytic emission control technology, fuel economy can be at its optimum for the 1975 Federal emission levels; hence a rollback of emission standards to pre-1975 Federal levels would not improve fuel economy. At best, it might make it easier (or cheaper) for those manufacturers with lower-than-average economy to come up to par.

To achieve emission levels significantly lower than the 1975 Federal standards, fuel economy penalties can be incurred if only the present technology is used; preservation of current optimum fuel economy levels requires the use of improved technology.

Many suitable technologies have been demonstrated in the laboratory, but require further development to assure adequate durability and reliability, and to permit production application of these technologies to the many different types of vehicles and engines that are produced. Some of these technologies have fuel economy potential that is at least as good as provided by the best 1975 emission control technology.

Effects of Tampering with Emission Control Systems

It is widely believed that fuel economy can be improved by tampering with emission controls on today's engines.

A research project was conducted to test this theory in actual practice; A number of 1973 and 1974 cars[a] were subjected to the following test sequence:

[a] Subcompact, compact, intermediate, and full-size cars were included.

- Tune to manufacturer's specifications and test for emissions and fuel economy;
- Consign to a private service garage with a request to "do whatever they could to improve fuel economy".
(Note: Emission control system tampering is illegal in more than half the States, but not as yet in Michigan; all modifications in this project were performed by Michigan garages.)
- Test for changes in fuel economy and emissions resulting from the garage tampering.
- Restore to manufacturer's specifications.

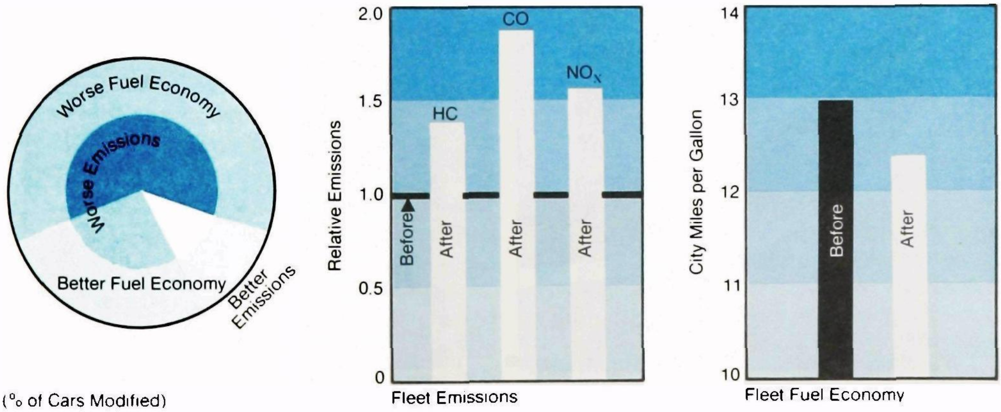
The garage modifications were performed by a variety of shops, including service stations, neighborhood garages, "speed shops", nationally-franchised tune-up centers, and foreign car specialists.

The main result of the project was that *both emissions and fuel economy were made worse* by the garage modifications, as illustrated in Figure 29.

About two-thirds of the cars lost fuel economy *and* increased in emissions. Less than 10% improved in both emissions and economy. It is interesting that no modification which improved emissions resulted in poorer fuel economy.

The effectiveness of the garage modifications did not vary much from shop to shop.

Figure 29—Effects of Private Garage Tampering



Of those shops which modified only one car, two out of every three made fuel economy worse; of those shops performing more than one modification, every one degraded the fuel economy of at least one of the cars it worked on.

The results of the project lead to the following conclusions:

- An attempt to improve fuel economy by tampering with emission controls is more likely to fail than to succeed. Few mechanics, even skilled ones, have the information necessary to fully understand emission control systems. (Even highly-skilled engineers trained in emission control technology and equipped with sophisticated instruments sometimes make fuel economy worse when they attempt to modify those parts that are adjustable.)

- Any massive effort to remove or modify emission controls on existing cars would result in *no net gain*, and probably some deterioration, in nationwide fuel economy. The only certain result of such an effort would be a major increase in motor vehicle emissions.

In addition to the specific conclusions above, these factors must be kept in mind:

- Today's auto engines have undergone changes in design to incorporate emission control systems. These changes are not readily reversible on existing engines.

- Where emission reductions have been achieved with specific devices or calibrations which could be "reversed", these modifications are so closely related to the basic changes in engine design that they cannot be varied independently.

- Some emission control systems and adjustments used on late-model engines improve fuel economy; removal or readjustment of such items can only result in simultaneous degradation of both emissions and economy.

- Carburetor settings, ignition timing, compression ratio, and exhaust gas recirculation all affect engine durability. Changes in these parameters to specifications other than those the engine was designed for can result in mechanical durability problems, performance problems, or both.

Benefits of Regular Tuneups

The discussion above dealt with the predominantly unfavorable results of

Figure 30—Fuel Economy of 1975 Models by Test Weight Class (Sales Weighted)

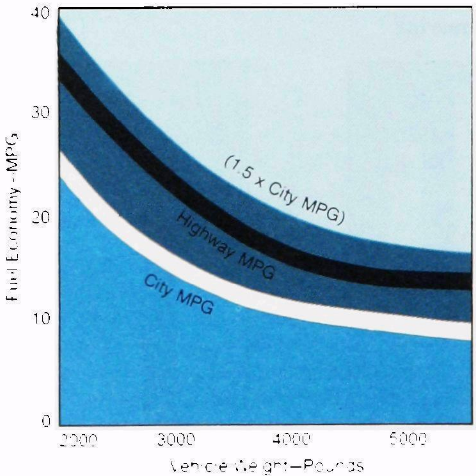
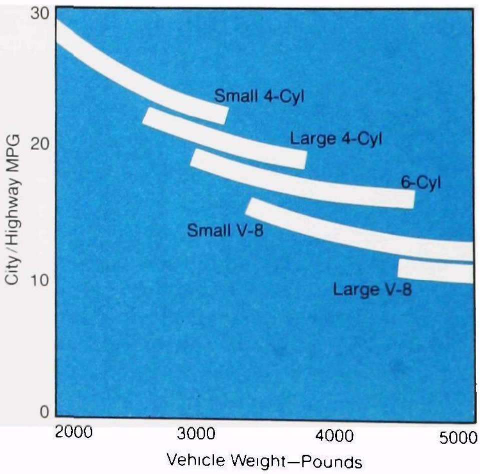


Figure 31—The Separate Effects of Vehicle Weight and Engine Size on 1975 Vehicles' Fuel Economy



tampering with properly-tuned engines. The other side of the coin involves the effects of performing manufacturer-recommended tuneups on as-received vehicles.

The tampering study also evaluated this aspect of engine adjustment on a small sample of cars.

Garage tune-ups improved both emissions (9%) and fuel economy (8%).

Thus, it appears on the whole that well-tuned cars are more likely to consume less fuel and emit less pollution than either untuned cars or cars with their emission controls deactivated.

Fuel Economy of 1975 Autos

As discussed in earlier sections of this report, fuel economy is determined by many factors. This section will illustrate 1975 fuel economy as a function of vehicle test weight class. Remember that vehicles in these weight classes differ from each other in more ways than weight: the heavier cars are larger in size, they use larger engines, and more of them use power-consuming accessories. So weight is not the only factor which causes the fuel economy differences between weight classes.

Figure 30 shows 1975 EPA city and highway fuel economy versus vehicle test weight. The values for each weight class are averaged in proportion to projected sales.

The average highway MPG for all weight classes is nearly 50% higher than the city MPG. This is consistent with the experience of many motorists in actual driving.

Figure 31 shows the separate *influences* of weight and engine size, when both are varied independently.

A change to a lower engine size in the same car can give a bigger fuel economy improvement than a 25% weight reduction with the same engine; a conservatively-powered standard size car can have fuel economy as good as, or better than, a high-performance compact car.

The composite MPG in Figure 31 was calculated for 55% city and 45% highway driving. (See Appendix C.)

For each engine size, the RPM characteristics as determined by axle ratio and tire size are held constant over the vehicle weight range used for that engine.

Figure 32—Late Models' Economy Compared to Pre-emission Control Models

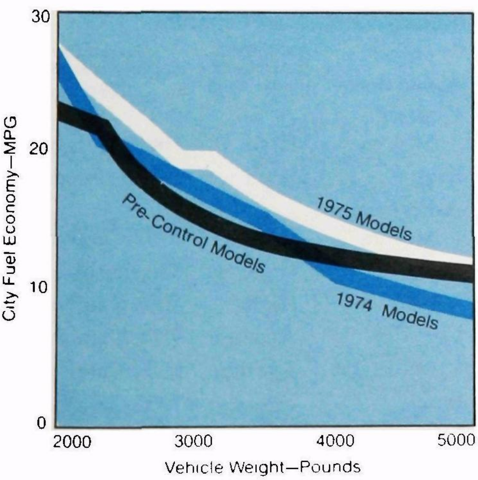


Figure 33—Fuel Economy of 1975 Catalyst and Non-catalyst Cars

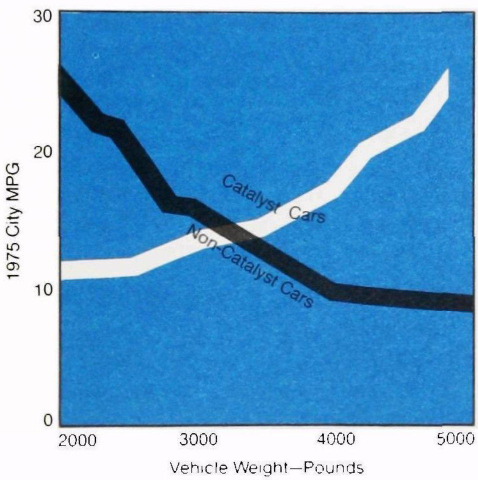


Figure 34—Variations in Fuel Economy with 1975 Catalyst Technology

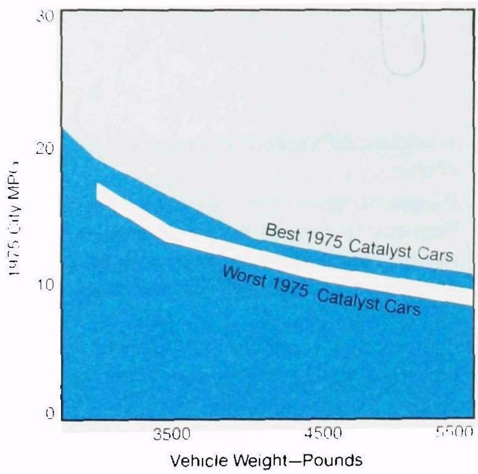
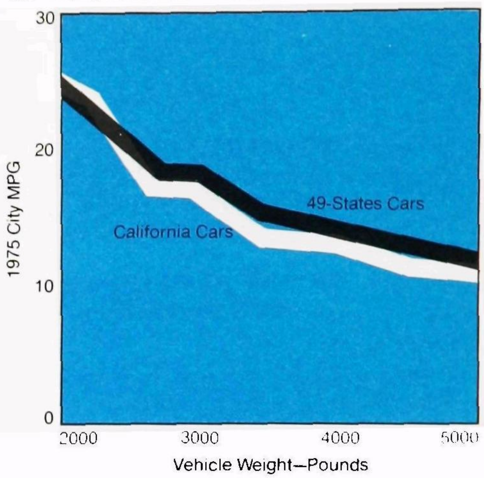


Figure 35—Economy of 49-States Models vs. California Models



Since the 1975 emission standards (and control technologies used to meet the standards) are different from previous years, the difference in fuel economy between 1975 cars and earlier models is of considerable interest.

Figure 32 shows that 1975 fuel economy is better than both pre-control and 1974 models.

The figure is based on the economy of individual makes and models averaged in proportion to projected sales. Changes from 1974 to 1975 are not the same for all manufacturers: some automakers have achieved large gains in economy, while others have lost ground. Since the "gainers" outnumber the "losers" in sales, the overall average has nevertheless increased. Table 5 lists the 1974 to 1975 gains and losses for ten individual manufacturers, as of October 1974.

If the data is subdivided according to the emission control approach used, it seems that catalyst-equipped cars, as a group, deliver better fuel economy than cars which use other control techniques, as depicted in Figure 33.

However, the mere presence of catalysts in a car line does not guarantee good fuel economy: As shown in Figure 34, the average of the best economy 1975 catalyst cars is significantly higher than the average of the worst-economy catalyst cars.

Conversely, the *absence* of catalyst usage does not necessarily mean poor fuel economy: many of the better fuel economy

Table 5

Overall Fuel Economy Change from 1974

Manufacturer	% Change in City MPG 1974 to 1975
Volkswagen	up 4%
Nissan	up 8%
Saab	up 24%
Peugeot	up 10%
American Motors	up 21%
Volvo	down 6%
BMW	down 11%
Chrysler	up 12%
General Motors	up 28%
Ford	down 2%
All Mfrs. together (Sales weighted)	up 13.8%

Table 6

Relative 1975 Fuel Economy

Manufacturer	1975 MPG Relative to Similar Cars	Overall Car Line Emission Control
General Motors	High	100% Catalyst
Saab	High	Engine Mods
American Motors	High	15% Catalyst
Peugeot	High	Thermal Reactor
Nissan	High	50% Catalyst
Chrysler	Average	95% Catalyst
Volkswagen	Average	65% Catalyst
Ford	Low	75% Catalyst
Volvo	Low	15% Catalyst
BMW	Low	Thermal Reactor

Figure 36—Typical Fuel Economy Label

Based on the results of tests conducted
or certified by the
U.S. ENVIRONMENTAL PROTECTION AGENCY,
the typical gas mileage of
this car is estimated to be:

Vehicle: Aardvark, 10 cylinder, 436 cubic inch displacement, 5 barrel carburetor, automatic transmission, catalyst equipped, air conditioning equipped.

10 MILES PER GALLON FOR CITY DRIVING

and

16 MILES PER GALLON FOR HIGHWAY DRIVING

These estimates are based on tests of vehicles equipped with frequently purchased optional equipment.

Reminder: The actual fuel economy of this car will vary depending on the type of driving you do, your driving habits, how well you maintain your car, optional equipment installed, and road and weather conditions. The use of overdrive provides approximately a 3% highway fuel economy improvement.

To compare the fuel economy of this car with other 1976 cars, and to learn how the tests were conducted, write for the *EPA/FEA 1976 Gas Mileage Guide for New Car Buyers,* to Fuel Economy, Pueblo, Colorado 81009.

1975 models (particularly in the lighter weight classes) achieved their optimum fuel economy without catalysts.

Table 6 compares the relative fuel economy and emission control approach for the same manufacturers listed earlier.

(Tables 5 and 6 are based on data that reflect fuel economy as of the date of the introduction of the 1975 models. These data can be expected to change as the manufacturers make technology improvements during the 1975 and subsequent model years.)

Table 7
Economy of California Models vs. 49-States Models

Manufacturer	1975 MPG, California vs. 49-States
Saab	Calif. Higher*
Volkswagen	Calif. Higher
Volvo	Calif. Higher
Ford	No Difference
Nissan	Calif. Lower*
Peugeot	Calif. Lower*
Chrysler	Calif. Lower*
General Motors	Calif. Lower*
American Motors	Calif. Lower*

* '75 Calif. higher than '74 49-states.

From table 6 and Figure 34 it is clear that a manufacturer's ingenuity in optimizing his overall engine system has more effect on fuel economy than the building blocks he chooses.

The data base was also divided into "California" and "49-States" groups. Many manufacturers produce two versions of their models—one version for sale in California, which has stricter 1975 emission standards, and another version for sale elsewhere in the U.S. Figure 35 shows the comparison between these groups.

Table 7 presents the California comparison by manufacturer. Again, the 1975 California versions tend toward lower economy than the 1975 49-States versions, but seven of the firms' 1975 California cars were as good or better than their 1974's.

For Information on Specific Models

Since the 1974 model year, EPA has sponsored a voluntary fuel economy labeling program, wherein manufacturers post on each new car the EPA-determined fuel economy of that model. Figure 36 is a typical fuel economy label. Most manufacturers are participating in the labeling program, and are using EPA fuel economy test results in advertising as well.

In addition, EPA and the Federal Energy Administration jointly publish each model year a *Gas Mileage Guide for New Car Buyers* which lists the fuel economy of each model of passenger cars and light duty trucks eligible for sale in the U.S.

A separate guide is published for California models.
For a copy of the *Mileage Guide*, write to:

Fuel Economy
Pueblo, Colorado 81009

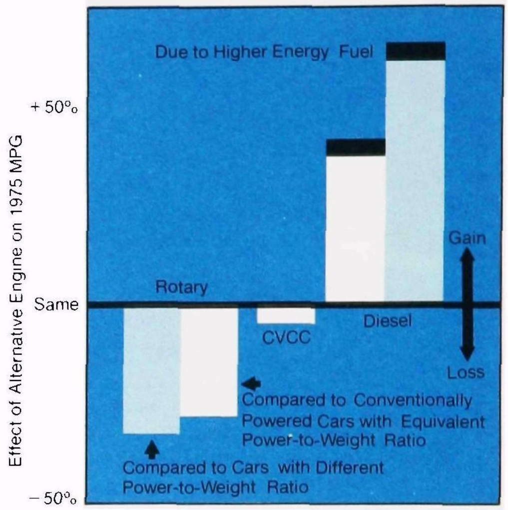
Alternative Engines

The conventional internal combustion gasoline engine must feel like the proverbial mousetrap: researchers are always trying to replace it with a better one. Each proposed alternative engine concept has its own advantages and its own particular disadvantages. Depending on the type of alternative engine, fuel economy can be "good" or "bad", compared to the conventional engine.

Three such engines are available in today's production automobiles: the rotary (Wankel), the CVCC stratified charge, and the diesel. The fuel economy of these engines is compared with conventionally-powered cars' economy in Figure 37, which shows that the rotary's fuel economy is worse, the CVCC's is about the same, and the diesel's is better.

For these engines, the comparison at equivalent power-to-weight ratios is valid for either city or highway MPG's.

Figure 37—Relative Fuel Economy of 1975 Alternative Engines



Other alternative engines being developed are: advanced versions of the stratified charge engine, and "continuous combustion" engines including the Rankine (vapor cycle) engine, gas turbines, Stirling engines, and others. Early experimental versions of these have frequently shown inferior fuel economy test results, but their proponents believe that further development will significantly improve these engines' fuel economy capabilities.

It is too early to reach firm conclusions about the feasibility of mass production of cars powered by these advanced alternative engines; the only certainty is that such engines will not see widespread use before the 1980's.

Bibliography

R. A. Matula, "Consultant Report (to the National Research Council) on Emissions and Fuel Economy Test Methods and Procedures", Washington, D.C.; September, 1974.

L. E. Furlong, E. L. Holt, and L. S. Bernstein, Esso Research and Engineering Co., "Emission Control and Fuel Economy" paper presented at American Chemical Society meeting, Los Angeles, Calif.; April, 1974.

U.S. Office of Education, Division of Manpower Development Training, "Vehicle Emission Control"; undated.

I. N. Bishop, Ford Motor Company, "Effect of Design Variables on Friction and Economy," SAE paper 812 A, January, 1964

L. E. Lichty, Yale University, "Internal Combustion Engines," McGraw-Hill, New York; 1939

C. F. Taylor and E. S. Taylor, Massachusetts Institute of Technology, "The Internal Combustion Engine," International Textbook Co., Scranton, Pa., 1948

C. F. Taylor, Massachusetts Institute of Technology, "The Internal Combustion Engine in Theory and Practice," Wiley and Sons, New York, 1960.

W. Smalley, Aerospace Corporation, "Passenger Car Weight Trend Analysis," report EPA-460/3-73-006a; January, 1974.

P. J. Claffey, "Running Costs of Motor Vehicles as Affected by Road Design and Traffic", National Cooperative Highway Research Program Report 111; 1971.

T. C. Austin and K. H. Hellman, U. S. Environmental Protection Agency, "Passenger Car Fuel Economy as Influenced by Trip Length," SAE paper 750004; February, 1975.

U.S. Environmental Protection Agency, "A Report on Automotive Fuel Economy," October, 1973.

Motor Vehicle Manufacturers Association, "Automobile Fuel Economy", September, 1973.

H. A. Ashby and R. C. Stahman, U.S. Environmental Protection Agency, B. H. Eccleston and R. W. Hurn, U.S. Department of the Interior, "Vehicle Emissions—Summer to Winter," SAE paper 741053, October, 1974.

J. P. DeKany and T. C. Austin, U.S. Environmental Protection, Agency, "Automotive Emissions and Energy Consumption," paper presented at Air Pollution Control Association Spring Seminar, Montebello, Quebec; May, 1974.

U.S. Environmental Protection Agency, "A Study of Fuel Economy Changes Resulting from Tampering with Emission Controls," Test and Evaluation Branch Report 74-21 DWP, January, 1974.

U. S. Department of Transportation and U. S. Environmental Protection Agency, "Potential for Motor Vehicle Fuel Economy Improvement—Report to the Congress," October 1974.

J. J. Gumbleton, R. A. Bolton, and H. W Lang, General Motors Corp., "Optimizing Engine Parameters with Exhaust Gas Recirculation," SAE paper 740104; February, 1974.

Appendix A

To calculate fuel economy, in miles per gallon (MPG), from an emission test, the following equation applies:

$$\frac{\text{Miles}}{\text{Gallon}} = \frac{\text{gms carbon/gal of fuel}}{\text{gms carbon in exhaust/mile}} \qquad \text{(A-1)}$$

The carbon in the fuel is:

$$\text{grams } C_{fuel} = \frac{\text{grams fuel}}{\text{gallon}} \times \frac{\text{molecular wt. C}}{\text{molecular wt. fuel}} \qquad \text{(A-2)}$$
$$= (2798) \times (.866)$$
$$= 2423$$

where:
2798 is the mean density of EPA test gasoline, in grams/gallons; and
.866 is the weight fraction of carbon in the fuel.

The carbon in the exhaust is contained in the unburned fuel hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2), as follows:

$$\text{grams } C_{HC} = \text{gm HC} \times \frac{\text{mol. wt. C}}{\text{mol. wt HC}} \qquad \text{(A-3)}$$
$$= \text{gm HC} \times (.866)$$
$$\text{grams } C_{CO} = \text{gm CO} \times \frac{\text{mol. wt. C}}{\text{mol. wt. CO}} \qquad \text{(A-4)}$$
$$= \text{gm CO} \times (.429)$$
$$\text{grams } C_{CO_2} = \text{gm } CO_2 \times \frac{\text{mol. wt. C}}{\text{mol. wt. } CO_2} \qquad \text{(A-5)}$$
$$= \text{gm } CO_2 \times (.273)$$

So we have:

$$\frac{\text{Miles}}{\text{Gallon}} = \frac{2423}{(.866\text{gmHC} + .429\text{gmCO} + .273\text{gmCO}_2)/\text{miles}}$$

or

$$\text{MPG} = \frac{2423 \times \text{miles traveled}}{.866\text{gmHC} + .429\text{gmCO} + .273\text{gmCO}_2} \qquad \text{(A-6)}$$

Example: In a 10-mile test, a car's exhaust emission measurements show the following amounts of carbon compounds:

HC — 9 grams
CO — 124 grams
CO_2 — 3641 grams

Using equation A-6, the fuel economy is:

$$\text{MPG} = \frac{2423 \times 10}{.866(9) + .429(124) + .273(3641)}$$
$$= \frac{24{,}230}{7.8 + 53.1 + 993.7} = 23.0 \text{ MPG}$$

Appendix B

Fuel economy can be expressed in terms of speed and fuel consumption rate, as follows:

$$\frac{\text{Miles}}{\text{Gallon}} = \frac{\text{Miles/Hour}}{\text{Gallons/Hour}} \qquad \text{(B-1)}$$

But fuel consumption rate is related to the engine power output (not the power rating) by the expression:

$$\frac{\text{Gallons}}{\text{Hour}} = \text{HP} \times \frac{\text{lbs (fuel)}}{\text{HP-Hr}} \times \frac{\text{Gals}}{\text{lb}} \qquad \text{(B-2)}$$

So fuel economy is:

$$\frac{\text{Miles}}{\text{Gallon}} = \frac{(\text{Mi/Hr}) \times (\text{lbs/gal})}{(\text{HP}) \times (\text{lb/HP-Hr})} \text{ or } \text{MPG} = \frac{\text{MPH} \times \text{Df}}{\text{HP} \times \text{SFC}} \qquad \text{(B-3)}$$

Where DF = fuel density, pounds per gallon (approximately 6.2 for gasoline); and
SFC = specific fuel consumption, pounds per hour per horsepower output.

SFC is a commonly-used engineering term directly related to engine efficiency. The more efficient an engine is, the less fuel it needs to deliver a given power output. For a typical gasoline fuel, the relationship between SFC and engine efficiency is:

$$\text{SFC} = \frac{13.5}{\text{Efficiency}} \qquad \text{(B-4)}$$

(An efficiency of 13.5% corresponds to an SFC of 1.0 1.0 lb/HP-Hr)

Substituting equation B-4 into B-3,

$$\text{MPG} = \frac{\text{MPH} \times \text{Df}}{\text{HP} \times 13.5/\text{Eff.}} = \frac{\text{MPH} \times 6.2 \times \text{Eff.}}{\text{HP} \times 13.5} \qquad \text{(B-5)}$$

So we see that fuel economy is a function of speed (MPH), engine load (HP), and engine efficiency according to:

$$\text{MPG} = .46 \frac{\text{MPH}}{\text{HP}} \times \text{Efficiency} \qquad \text{(B-6)}$$

for a typical gasoline fuel.

Example: An intermediate size car requires an engine output of 26 HP to cruise at 50 MPH. The engine efficiency for this condition is 22.0% (SFC = 0.614) Using equation B-6, the fuel economy is:

$$\text{MPG} = .46 \times \frac{50}{26} \times 22.0 = 19.5 \text{ MPG}$$

To cruise at 70 MPH, the same car requires 51 HP, and the engine efficiency is 25.4% (SFC = 0.532). The fuel economy is:

$$\text{MPG} = .46 \times \frac{70}{51} \times 25.4 = 16.0 \text{ MPG}$$

Appendix C

Suppose a motorist takes the following trips:

200 miles, using 15.0 gallons;
100 miles, using 9.4 gallons;
140 miles, using 11.8 gallons.

The fuel economies of these trips are:

$$\frac{200 \text{ miles}}{150. \text{ gal.}} = 13.3 \text{ MPG};$$
$$\frac{100 \text{ miles}}{9.4 \text{ gal.}} = 10.6 \text{ MPG};$$
$$\frac{140 \text{ miles}}{11.8 \text{ gal.}} = 11.9 \text{ MPG}.$$

If he merely averages the trip MPG's, he gets:

$(13.3 + 10.6 + 11.9) \div 3 = 11.9$ MPG

But this is incorrect. The motorist traveled 440 miles and used 36.2 gallons, so his overall fuel economy was:

$440 \div 36.2 = 12.2$ MPG

To get the correct fuel economy for multiple trips, the following equation must be used:

$$\frac{\text{Miles}}{\text{Gallon}} = \frac{\text{total miles traveled}}{\text{total gallons used}} \qquad \text{(C-1)}$$

If the individual trip lengths and fuel economy values are known, but the gallons used are not known, the proper equation is:

$$\text{MPG} = \frac{\text{miles}_1 + \text{miles}_2 + \ldots + \text{miles}_N}{\frac{\text{miles}_1}{\text{MPG}_1} + \frac{\text{miles}_2}{\text{MPG}_2} + \ldots + \frac{\text{miles}_N}{\text{MPG}_N}} \qquad \text{(C-2)}$$

where miles_x = length of trip "x";
MPG_x = gas mileage for trip "x"; and
N = number of trips.

For a number of test trips *of the same length*, equation C-2 is equivalent to:

$$\text{MPG} = \frac{\text{miles}_t \times N}{\text{miles}_t \left(\frac{1}{\text{MPG}_1} + \frac{1}{\text{MPG}_2} + \ldots + \frac{1}{\text{MPG}_N}\right)} \qquad \text{(C-3)}$$

where miles_t = the standard test length and
N = the number of tests.

Equation C-3 simplifies to:

$$\text{MPG} = N \div \Sigma_N \left(\frac{1}{\text{MPG}_N}\right) \qquad \text{(C-4)}$$

which is the "harmonic average" of the MPG's from the test.

To calculate the composite MPG from known city and highway MPG's, the apportionment of total mileage between city and highway driving must be used. If a motorist drives 55% of his mileage in the city and 45% on the highway, his composite fuel economy is:

$$\text{MPG} = \frac{\text{total miles}}{\frac{.55(\text{total miles})}{\text{City MPG}} + \frac{.45(\text{total miles})}{\text{Highway MPG}}}$$
$$= \frac{1}{\frac{.55}{\text{MPG}_C} + \frac{.45}{\text{MPG}_H}} \qquad \text{(C-5)}$$